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THE REFLECTION EFFECT IN HZ HERCULES

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Recently Davidsen, Henry, Middleditch, and Smith (1972) and Forman, Jones, and Liller (1972) have published photometric observations of the x-ray eclipsing system HZ Hercules (= Her X-1). Forman, et. al. interpreted the 1.5 magnitude brightness variation as due to the usual binary star reflection effect taking place on the relatively large optical component, with the source of energy being the compact x-ray source. While it seems scarcely conceivable that the variation is due to something other than reflection, there does exist a major difficulty for straightforward acceptance of this idea. The problem is that the theoretical phase law for the "relected" light from a rotating binary component is so completely at variance with the observed light curves that the discord can easily be seen even from the photographic observations of Forman, et. al. A convenient summary of early theoretical work on the phase law for reflection can be found in Russell and Merrill (1952). A law by Milne (1926), as modified by Sen (1948) to account for the finite distance of the energy source, is adequate for HZ Her, where the irradiating energy is emitted by a point source. Assuming a value of 0.4 for r_1/a, the radius of the optical component relative to the component separation, the Milne-Sen phase law for orbital inclination 90° is;

$$f(\theta) = 0.314 + 0.447 \cos\theta + 0.153 \cos 2\theta + 0.005 \cos 3\theta - 0.006 \cos 4\theta$$

Checks made with the binary star program of Wilson and Devinney (1971) show that this relation is not modified very much by tidal distortion or by inclinations less than 90°, provided that i is not less than about 65°. Of course, the constant term will be larger than 0.314 if there are constant sources of light in the system, and a value of 0.9 was used in the present computations.

Figure 1 compares the Milne-Sen law with the (mostly) photoelectric B observations by Davidsen, et. al. The flat region in the Milne-Sen law is due to the fact that only one region of the star has a strong brightness variation, and this part is out of sight when we view the dark side. The observations show an effect quite opposite to that of the theoretical law - there is a sharp downward spike at just the phase where there should be a broad minimum, while the maximum is much more gently curved than the theoretical law. The photographic observations (Forman, et. al.) also differ clearly from the theoretical law but, due to their scatter, the disagreement is somewhat less striking. Remarkably, the Milne-Sen law agrees almost reasonably well with the observations if it is shifted 180° and

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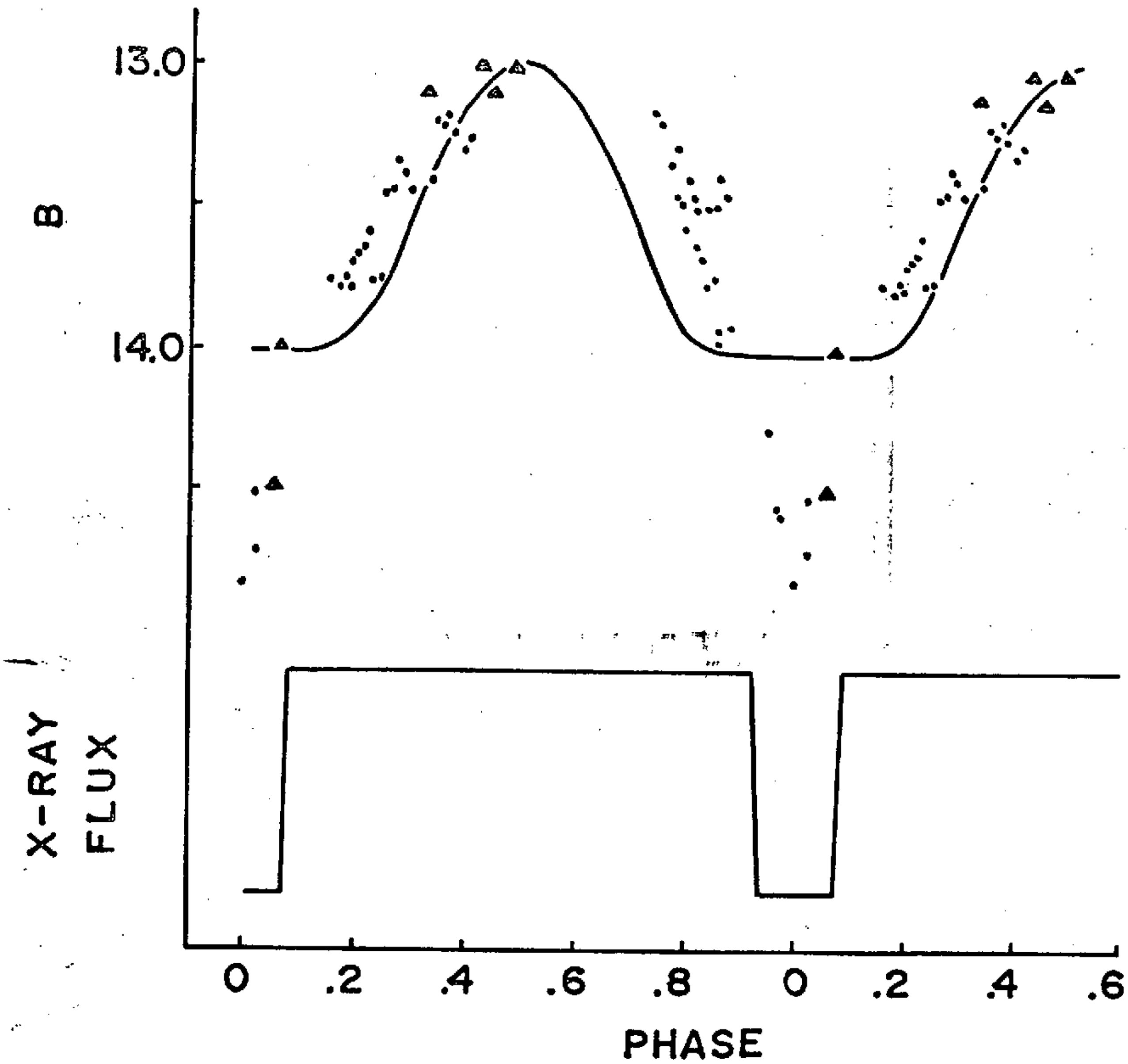

inverted (turned upside down)! Since the observed light curves show all the gross features of the reflection effect (maxima at x-ray phase 0.5, minima at phase 0.0; approximate symmetry about phases 0.0 and 0.5) and the spectral type and color index vary as expected, it seems certain that the basic interpretation by Forman, et. al., is correct. Nevertheless it is entirely impossible for the reflection effect, as encountered in normal binaries, to show the phase dependence observed for HZ Her.

We might try to explain the spike at minimum as due to the eclipse of a large, optically emitting region surrounding the x-ray star, although it is difficult to imagine how the x-rays would escape if such a region were present. However, this idea cannot explain the failure of the Milne-Sen law to fit the observations at other phases, such as the maximum. At first sight it would seem that the improved agreement found upon inverting the theoretical phase law is merely coincidental and should not be given any particular interpretation. However, it is instructive to ask what geometrical situation corresponds to turning the phase law upside-down. This operation provides the phase law for the <u>photographic negative</u> of a motion picture of the rotating component. That is, if we replace each (relatively) bright element of area on a normal reflecting star with an element which is relatively dark, and vicc-versa, the inverted Milne-Sen law would be a good approximation to the resulting light curves. Now an ordinary binary component which shows a strong reflection effect has a very bright cap whose intensity diminishes rapidly for points successively farther from the sub-stellar point. For practical purposes it can be said that the bright region extends substantially less than halfway around thc star, since both the inverse square law and a projection factor greatly diminish the heating effect at the "sides" of the star. The primary of HZ Her behaves as if it were the negative image of such a normal reflecting component. Therefore we expect it to have a very dark cap on one end which extends <u>less than halfway</u> around the star. Interpreting this dark cap as the anti-sub-stellar point, it appears that the actual reflection effect extends substantially <u>more than</u> halfway around the star, a situation which would seem to be geometrically impossible since the back hemisphere is not in view of the x-ray source. We are forced to conclude that the large x-ray flux drives circulation currents which redistribute the incident energy over a considerable part of the surface which is not exposed to direct x-radiation. Furthermore, these circulation currents cannot be superficial surface currents, since the characteristic time for radiation of the heat content of the surface layers is not longer than a few minutes, even under the most extreme assumptions, and this time scale would not allow adequate time for transfer of the energy over the surface. We conclude that a major fraction of the envelope must be affected by the x-ray flux, that circulation currents carry energy into the interior, and that this energy subsequently appears at points of the surface which are more than half-way around the star from the sub-stellar point. It has already been shown by Rucinski (1969) that for stars with convective envelopes, the bolometric albedo should be only about 0.4 to 0.5 rather than unity, because the incident flux disturbs the envelope to quite deep layers. Such values for the bolometric albedo have been found from observations of several binaries (e.g. Napier, 1970; Wilson, et. al. 1972).

Forman, et. al. have estimated the undisturbed spectral type of the optical component to be middle F, and this estimate would be too early if some of the back hemisphere is effectively heated by the x-rays. Therefore we definitely can expect a deep convective envelope for this star, and it should be most useful to construct a model for its interior structure.

Caption for Figure 1

The expected phase law for a normal reflection effect (solid curve) compared with the B light curve of HZ Her by Davidsen, Henry, Middleditch, and Smith. Most observations are photoelectric (dots). A few photographic observations are shown as triangles.

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